

Disentangling surface and bulk transport in topological insulator p - n junctions

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By combining n -type Bi_2Te_3 and p -type Sb_2Te_3 topological insulators, vertically stacked p - n junctions can be formed, allowing to position the Fermi level into the bulk band gap and also tune between n - and p -type surface carriers. Here we use low-temperature magnetotransport measurements to probe the surface and bulk transport modes in a range of vertical $\text{Bi}_2\text{Te}_3/\text{Sb}_2\text{Te}_3$ heterostructures with varying relative thicknesses of the top and bottom layers. With increasing thickness of the Sb_2Te_3 layer we observe a change from n - to p -type behavior and a specific regime where the Hall signal is immeasurable. We develop a multichannel conductance model which has the mobility of the topological surface state as the only fitting parameter. The model correctly anticipates the dependence of the Hall and longitudinal components of resistivity. Furthermore, it predicts the compensation of n - and p -type contributions at a specific composition, where indeed the resistance is very high and, simultaneously, the Hall signal is immeasurable. Lastly, it explains why the alignment of Fermi level and Dirac point do not coincide with the suppression of bulk conduction. Our results provide crucial experimental and theoretical insights into the relative roles of the surface and bulk in the vertical topological p - n junctions and establish them as viable low- ρ counterparts to alternative bulk-compensated topological insulators.

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Topological insulators (TIs) are bulk insulators with exotic ‘topological surface states’ [1] (TSSs) which are robust to backscattering from non-magnetic impurities, exhibit spin-momentum locking [2] and have a Dirac-like dispersion [3–5]. These unique characteristics present several opportunities for applications in spintronics, thermoelectricity, and quantum computation due to which TIs have received much recent attention. However, a major drawback of ‘early generation’ TIs such as $\text{Bi}_{1-x}\text{Sb}_x$ [5] and Bi_2Se_3 [2, 3] is that the Fermi level E_F intersects the conduction/valence bands, thus giving rise to finite conductivity in the bulk. This non-topological conduction channel conducts in parallel to the TSSs and in turn subverts the overall topological nature. Thus, in order to create bona fide TIs, the Fermi level E_F needs to be tuned within the bulk bandgap, and this has previously been achieved by means of electrical gating [6–9], doping [4, 10–12], or, as recently reported, by creating p - n junctions from two different TI films [3, 13].

In Ref. [3] a ‘vertical topological p - n junction’ was realised by growing an n -type Bi_2Te_3 layer capped by a layer of p -type Sb_2Te_3 . It was shown that varying the p -layer thickness serves to tune E_F and this was exploited towards controlling the TSS carrier type without the use of an external field [3]. Importantly, such bilayer systems are expected to be significantly less disordered than doped materials such as $(\text{Bi}_{1-x}\text{Sb}_x)_2\text{Te}_3$ in which E_F can lie within the bulk band gap, but where inhomogeneity of the dopants is a constant problem [12, 15]. Furthermore, and in sharp contrast to doped TIs, the intrinsic p and n character of the individual layers allows for the sponta-

neous existence of an n -type and a p -type TSS on adjacent sides of a single TI slab [16]. This in turn presents remarkable opportunities towards the observation of novel excitonic interactions between Dirac fermions including Klein tunneling [17, 18], or exotic quantum states such as the topological exciton condensate [19]. However, currently there exists little understanding of the bulk conduction in such topological p - n junctions, primarily because the angle-resolved photoemission spectroscopy (ARPES) used in Ref. [3] to probe them is a surface-sensitive method. This is especially noteworthy in light of the varying band structure within the TI slab which is a prominent difference from the essentially constant band gap within the bulk of $(\text{Bi}_{1-x}\text{Sb}_x)_2\text{Te}_3$ -type compounds. Understanding and minimizing the bulk conduction channels in TI p - n junctions is crucial in order to realize their technological potential and also in order to gain access to the exotic physics they can host.

In this Letter, we report low-temperature (low- T) magnetotransport measurements on Hall bars lithographically patterned on to p - n junctions similar to those reported in Ref. [3]. We measure and analyse the longitudinal and Hall components of resistance (R_{xx} and R_{xy} , respectively) and, as expected, find a change from n -type to p -type charge carriers as the thickness of the p -type layer is increased. Interestingly, we also encounter a specific ratio of thicknesses in which there is *no measurable Hall signal*, indicating a near perfect cancellation of p and n contributions. Unexpectedly, however, this occurs at a thickness ratio *different* to that in which ARPES measurements reveal E_F to intersect the Dirac point [3].

We ascribe this difference to the uncompensated charges in the bulk which cannot be discerned using ARPES. Finally, we understand the relative roles of the bulk and surface by means of a simple model of the Hall coefficient in a multi-channel system. The model correctly predicts the Hall coefficient for the range of $\text{Sb}_2\text{Te}_3/\text{Bi}_2\text{Te}_3$ heterostructures explored here using only a single fitting parameter, namely the mobility of the TSS. In particular, it predicts that the *effective* carrier concentration goes to zero precisely where the Hall slope is intractable. With further refinement the model is also able to predict R_{xx} of the heterostructures, thus providing insights into the bulk conduction which, in turn, yields a better understanding of the origin of the much-debated high-field linear MR [20–25] often observed in Dirac materials.

$\text{Bi}_2\text{Te}_3/\text{Sb}_2\text{Te}_3$ -bilayers (BST) were grown on phosphorous doped Si substrates using molecular beam epitaxy (MBE) in an ultrahigh vacuum chamber. In all the samples, the bottom Bi_2Te_3 -layer had thickness $t_{\text{BiTe}} = 6 \text{ nm}$ while the top Sb_2Te_3 -layers had thicknesses $t_{\text{SbTe}} = 6.6 \text{ nm}$ (BST6), 7.5 nm (BST7), 15 nm (BST15), and 25 nm (BST25), respectively. In fact, the samples used for this work stem from the same growth process and have the same materials parameters as samples previously used for ARPES measurements (see Ref. [3]). Subsequently, the layers were patterned into Hall bars of width $W = 200 \mu\text{m}$ and length $L = 1000 \mu\text{m}$ using photoresist as a mask for ion milling, and Ti/Au contact pads were deposited for electrical contact. Low- T , low-noise transport measurements were carried out using lock-in techniques in a He-3 cryostat with a base temperature of 280 mK and a 10 T superconducting magnet.

Figure 1(a) shows the longitudinal magnetoresistance (MR) $\equiv (R_{xx}(B) - R_{xx}(0))/R_{xx}(0)$ of the various samples considered. We find that above $\sim 2 \text{ T}$ the MR in BST6 and BST7 is linear with no obvious indication of the Lorentz-force induced B^2 -dependence [26]. The MR in BST15 and BST25, on the other hand, appears to be neither purely linear or quadratic. While there is experimental evidence suggesting an association between linear MR and linearly dispersive media [20–22], as well as a theoretical basis for this association [23], we note that disorder can also render giant linear MR [24, 25] by admixing longitudinal and Hall voltages.

In Fig. 1(b) we see that R_{xy} is linear in B and its slope changes sign from positive (BST6) to negative (BST15 and BST25). This is simply a reflection of different charge carrier types of Bi_2Te_3 (n -type) and Sb_2Te_3 (p -type), where electrons (holes) dominate transport when Sb_2Te_3 is thin (thick). On the contrary, Fig. 1(c) shows R_{xy} vs B measured in two different Hall bar devices of BST7 to be both non-linear and non-monotonic, and clearly offset from the origin. Qualitatively, it appears as though R_{xy} is picking up a large component of R_{xx} despite the Hall probes being aligned to each other with lithographic (μm -scale) precision. We conclude, there-

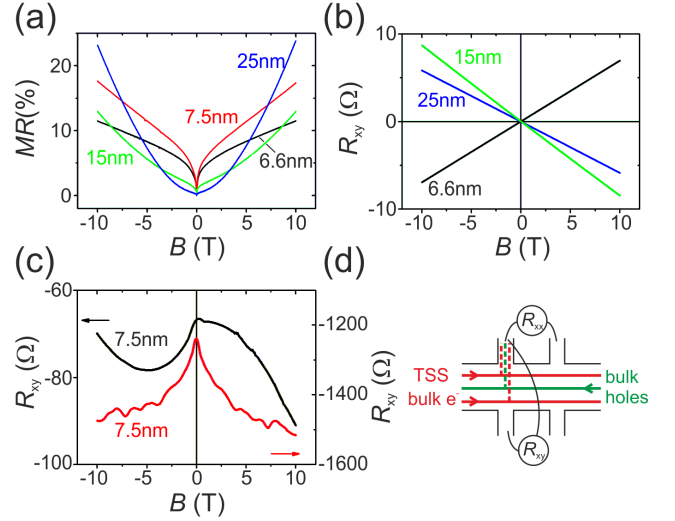


FIG. 1. (a) Magnetoresistance (MR) and (b+c) Hall resistance R_{xy} as a function of an out-of-plane magnetic field for different thicknesses of the Sb_2Te_3 layer. All curves are measured at 280 mK. The high field behavior of R_{xx} is linear for thin and changes to parabolic for thick Sb_2Te_3 . Cusp-like deviations at low fields are due to WAL corrections. The sign change of the slope in (b) indicates transport by electrons for BST6 and by holes for BST15 and BST25. No Hall slope is visible in (c) for 2 different pairs of contacts of BST7. (d) The schematic shows the charge transport channels in a longitudinal and transverse measurement setup. Trajectories of TSS and bulk electrons are shown in red and of bulk holes in green color.

fore, that BST7 is very close to where R_H precisely changes from positive to negative. Interestingly, ARPES measurements in Ref. [3] reveal that E_F intersects the Dirac point in samples with $15 \text{ nm} < t_{\text{SbTe}} < 25 \text{ nm}$, in which parameter regime Fig. 1(b) indicates a net excess of p -type carriers. The origin for this complicated behavior is the interplay of bulk and surface transport channels of opposite charge types, and their influence on R_{xx} and R_{xy} is schematically depicted in Fig. 1(d).

In the following, we first determine the number of participating TSSs and subsequently develop a model to describe the behavior of R_{xx} and R_{xy} . In order to estimate the number of TSSs, we examine the ‘weak antilocalisation’ (WAL) characteristics as well as signatures of electron-electron interactions (EEI) in the transport. The WAL cusp observed at low- B for all the devices in Fig. 1(a) is indicative of positive quantum corrections to the conductance arising due to the π -Berry phase of the TSSs [27] and/or the strong spin-orbit coupling in the bulk of the TIs [28]. We find that these corrections are well-described by the model of Hikami, Larkin and Nagaoka (HLN) [1] from which we obtain the number of 2D WAL channels 2α and the phase coherence length l_ϕ as fitting parameters. WAL measurements and a description of the fitting procedure can be found in the

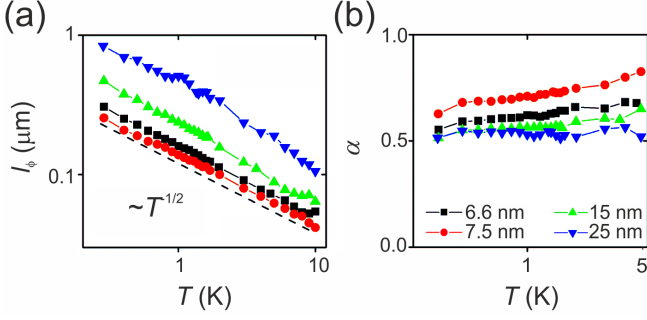


FIG. 2. (a) Phase coherence length l_ϕ as a function of the temperature T for various Sb_2Te_3 layer thicknesses in a double-logarithmic plot. All curves are proportional to $\propto T^{-0.5}$ (dashed line) but shifted with respect to each other. (b) α as a function of the temperature T for various Sb_2Te_3 layer thicknesses.

Supplemental Material [30].

Figure 2(a) shows the T -dependence of l_ϕ for all samples. We find that $l_\phi \propto T^{-p/2}$, where the exponent $p = 1$ is in line with 2D Nyquist scattering [31, 32] due to electron-electron scattering processes. We also note in this context that l_ϕ is always larger than the sample thickness. The second fitting parameter α is depicted in Fig. 2(b) and we find values consistent with the existence of only one TSS. Importantly, and in agreement with the behavior of R_{xy} , Fig. 2 shows l_ϕ to be non-monotonic in t_{SbTe} , being smallest for BST7.

While WAL manifests as positive corrections to the conductivity, EEIs serve to suppress it [31]. We find evidence for this in the inset to Fig. 3(a) which shows R_{xx} as a function of T to crossover from metallic ($dR_{xx}/dT > 0$) to insulating ($dR_{xx}/dT < 0$) behavior at a characteristic temperature T^* (indicated by the arrow; see also Figs. 3(a)-(d) in [30]). Figure 3(a) shows T^* to be non-monotonic in t_{SbTe} with the largest observed value for, again, BST7. We contrast this behavior to that reported by Liu *et al.* [33] in ultrathin Bi_2Se_3 -layers in which the characteristic temperature decreased monotonically with film thickness due to the decreasing contribution of bulk states. Figure 3(b) shows that $\sigma_{xx} \equiv (L/W)R_{xx}/(R_{xx}^2 + R_{xy}^2)$ has a logarithmic dependence on T for different B which is the expected dependence in 2D in the presence of WAL and/or EEI. In 2D the conductivity corrections due to EEI assume the following form [34]

$$\delta\sigma(T) = -\frac{e}{\pi h}n \left(1 - \frac{3}{4}F\right) \ln\left(\frac{T}{T^*}\right) \quad (1)$$

where $f = n(1 - \frac{3}{4}F)$ is the amplitude of the logarithmic T dependence, n is the number of 2D channels contributing to EEI, and F the screening factor. Fitting the data in Fig. 3(b) to Eq. 1 we find that f saturates by 0.2 T (see Fig. 3(c)) indicating the dephasing of the TSS and

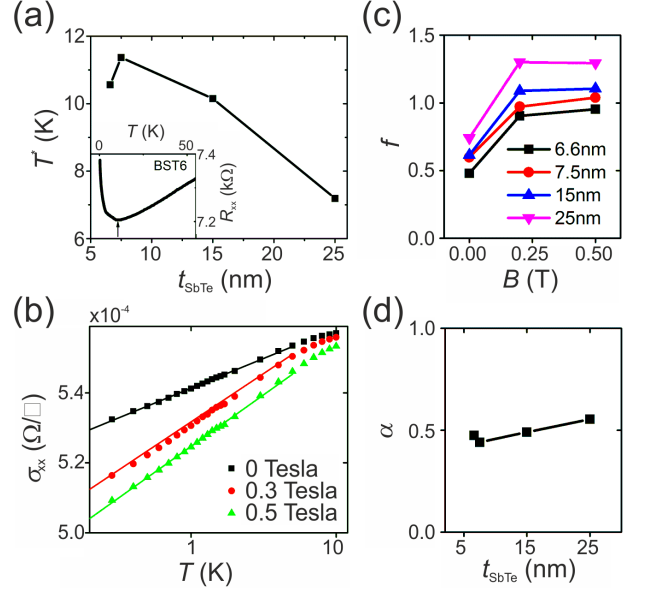


FIG. 3. (a) Crossover temperature T^* as a function of Sb_2Te_3 thickness. The inset shows the resistance during cooldown from which T^* is obtained. (b) Temperature dependence of σ_{xx} for BST7 and 3 different B -fields. Fits based on equation 1 are plotted with straight lines. (c) Fitting parameter f as a function of magnetic field for all Sb_2Te_3 -thicknesses. (d) α obtained from the field dependence of f in (c).

consequent suppression of WAL. The difference between the saturated and zero field amplitude $\Delta f = p \cdot \alpha$ [34] and using $p = 1$ as determined in Fig. 2(a), we obtain $\alpha \approx 0.5$ as shown in Fig. 3(d). Thus both the WAL and EEI characteristics suggest $\alpha \approx 0.5$, i.e., that only one TSS is present at all thicknesses. Since a TSS on the top surface has been confirmed using ARPES [3], we conclude that the TSS on the bottom layer must be disrupted.

Having established that the Hall slope changes in the vicinity of $t_{\text{SbTe}} = 7.5$ nm and having ascertained that only one TSS contributes to the transport, we are now in a position to explain the complex interplay of bulk and TSS. Our starting point is the expression for the Hall coefficient in a multi-channel system [2]:

$$R_H \equiv \frac{1}{e \cdot n_{\text{eff}}} = \frac{\sum_i (1/q_i) n_i \mu_i^2}{(\sum_i n_i \mu_i)^2}. \quad (2)$$

Here n_{eff} is the effective carrier concentration, $q_i = e$ for electrons and $-e$ for holes (e itself is negative), n_i is the carrier concentration and μ_i is the mobility of the i th channel and $i \in \{n, p, t\}$ corresponding to the bottom (n -type) Bi_2Te_3 layer, the top (p -type) Sb_2Te_3 layer, and the TSS, respectively. The following literature values for the bulk layers are used: $n_{\text{BiTe}} = 8 \times 10^{19} \text{ cm}^{-3}$ and $\mu_n = 50 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ for Bi_2Te_3 [12] and $n_{\text{SbTe}} = 4.5 \times 10^{19} \text{ cm}^{-3}$ and $\mu_p = 300 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ for Sb_2Te_3 [12, 32, 36]. In order to meaningfully compare n_{BiTe}

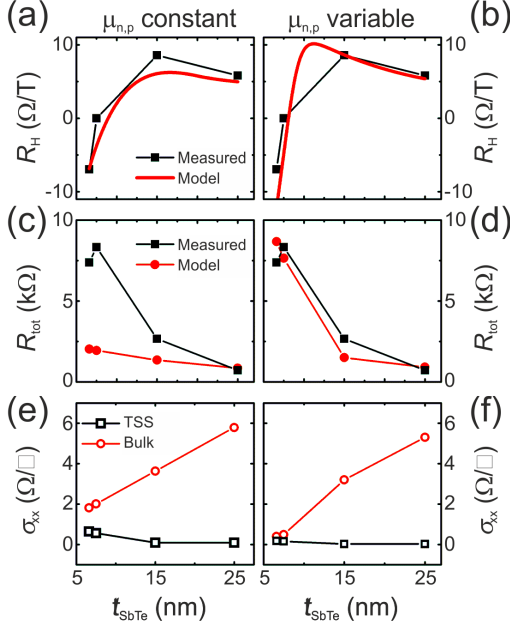


FIG. 4. (a+b) Hall slopes R_H determined from the Hall measurements in Fig. 1(b) (black square), and fitted using Eq. 3 (red lines). The bulk mobilities $\mu_{n,p}$ were kept constant in (a) and reduced for low thicknesses in (b). (c+e) Comparison of measured (black squares) and calculated total resistance (red disks), and conductivity of the TSS (black open squares) and of the bulk (red open disks), using fitting parameters from (a). (d+f) Same as (c+e) but using fitting parameter from (b). All variables are a function of the Sb_2Te_3 -thickness.

and n_{SbTe} to the TSS carrier concentration, we convert them to effective areal densities as $n_n \equiv n_{\text{BiTe}} \cdot t_{\text{BiTe}}$ and $n_p \equiv n_{\text{SbTe}} \cdot t_{\text{SbTe}}$. The carrier concentration of the TSS $\propto E_B^2$ where the binding energy E_B is the difference between E_F and Dirac point (see Supplemental Material [30]). E_B can be retrieved from ARPES measurements in Ref. [3] and n_t can be shown to scale as t_{SbTe}^2 (see Eq. 5 in [30]). Substituting the above in Eq. 2 we obtain R_H as a function of the varying t_{SbTe} layer:

$$R_H(t_{\text{SbTe}}) = \frac{n_p \mu_p^2 \pm n_s(t_{\text{SbTe}}) \mu_t^2 - n_n \mu_n^2}{e(n_p \mu_p + n_s(t_{\text{SbTe}}) \mu_t + n_n \mu_n)^2} \quad (3)$$

The ‘-’ sign is for negative ($t_{\text{SbTe}} < 20$ nm) and the ‘+’ sign for positive charge carriers ($t_{\text{SbTe}} > 20$ nm) in the TSS. The derivation of

R_H calculated from Eq. 3 is plotted in Fig. 4(a) (straight red line), together with the measured values (black squares). We note that with just a single fitting parameter μ_t , the model captures the broad physics namely that R_H changes sign at around $t_{\text{SbTe}} \approx 10$ nm and there is reasonable quantitative agreement overall. This is clearly consistent with the observation of ‘no’ Hall slope in BST7.

Using the individual μ_i and n_i of all three channels, we are now able to construct the net resistance R_{tot} using $R_{\text{tot}}^{-1} = (L/W) \sum_i (1/e n_i \mu_i)$ (Fig. 4(c)), as well as differentiate between the bulk and surface contributions (Fig. 4(e)). However, we find that while there is reasonable agreement between the measured and predicted R_{xx} at large t_{SbTe} , the model is not adequate for low t_{SbTe} where the model significantly underestimates R_{xx} .

Intuitively it can be argued that the literature values of μ for the Bi_2Te_3 and Sb_2Te_3 layers will overestimate the thin film mobility. This is further exacerbated by the fact that a depletion zone must exist at the p - n interface which will induce a further reduction in μ [15]. Based on these physical arguments and noting that they should affect the thinner layers more, we introduce an *ad hoc* thickness-dependent reduction of the mobility of both bulk layers with all other parameters unchanged and μ_t still the only fitting parameter. Figure 4(b) shows the result of a fit in which μ_p and μ_n are reduced to 20% of their bulk value in BST6 and BST7, and to 95% of their bulk value BST15 and BST25. Not only do we obtain excellent agreement with the R_H data, the model is also able to accurately predict R_{xx} . The obtained value of $\mu_t = 180 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ is well within the range of previous studies in ultra-thin TIs where the TSSs dominate transport [11]. Notably, the quality of the fit relies on the important physical insight that the bulk contribution is drastically reduced in thin films, and not simply due to the increased surface-to-volume ratio.

We now return to the question of the linear magnetoresistance. Clearly, the linearity appears when the bulk conductivity is decreased and thus most pronounced in BST6 and BST7 (see Figs. 1(a) and 4(f)). If, indeed, the bulk mobility is sharply reduced in the thinner films, then it can be argued that the observed linear magnetoresistance is a disorder effect. However, for BST6 and BST7 in Fig. 1(a) the magnitude of the MR is anti-correlated to the film thickness, i.e., BST6 which should have the higher degree of bulk disorder, has a lower MR than BST7. We emphasize that the capability of our method to disentangle the relative roles of the bulk and surface in TIs, can be crucial towards the understanding of linear MR.

In conclusion, we have reported low- T magnetotransport measurements on vertical topological p - n junctions and understood the data within a three-channel model for the Hall resistance. This provides useful insights into the complex interplay of bulk states and TSS in the multilayered TI structures, explains the sign change of R_H with varying t_{SbTe} , and delivers values for the mobility of the TSS of $180 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$. Our work paves the way for the study of other complex TI heterostructures [37, 38], where bulk states and TSSs of different carrier types co-exist. Low- T transport measurements are a powerful tool for the examination of TI multilayers, delivering not only information about topological transport, but also about

electron-electron interactions. In future, our method can be applied to improved topological p - n junctions in which the top and bottom TSS are present and can form novel Dirac fermion excitonic states.

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SUPPLEMENTAL MATERIAL

In this supplement we discuss the methods and models used for the analysis of the transport data and present additional measurements which corroborate our findings presented in the main text.

Analysis of weak antilocalization peaks

The 2-dimensional longitudinal conductance exhibits pronounced peaks at magnetic fields < 0.3 T. Example measurements for different sample thicknesses and temperatures are depicted in Fig. S1. We find that these corrections are well-described by the model of Hikami, Larkin and Nagaoka (HLN) [S1] and obtain the number of 2D WAL channels α and the coherence length l_ϕ as fitting parameters.

$$\Delta\sigma_{xx}^{2D} \equiv \sigma_{xx}^{2D}(B) - \sigma_{xx}^{2D}(0) = \alpha \frac{e^2}{2\pi^2\hbar} \left[\ln \left(\frac{\hbar}{4eBl_\phi^2} \right) - \psi \left(\frac{1}{2} + \frac{\hbar}{4eBl_\phi^2} \right) \right] \quad (\text{S1})$$

Here $\sigma_{xx} \equiv (L/W)R_{xx}/(R_{xx}^2 + R_{xy}^2)$ and the superscript 2D indicates that the equation is valid for a two-dimensional conducting sheet, α is a parameter = 0.5 for each 2D WAL channel, e is the electronic charge, \hbar is Planck's constant divided by 2π , l_ϕ is the phase coherence length, and ψ is the digamma function. We use Eq. S1 to fit a range of WAL peaks measured for different Sb_2Te_3 -thicknesses at different temperatures (see Fig. S1) using α and l_ϕ as fitting parameters.

TSS electron density from ARPES measurements

The density of states in the dirac cone [S2] is given by

$$g(k)dk / \frac{2\pi^2}{L} = 2\pi k dk / \frac{2\pi^2}{L} = \frac{k dk}{(2\pi/L)^2} \quad (\text{S2})$$

The relation between the binding energy E_B , i.e. the difference between the Fermi energy and the Dirac point, and the Fermi wave vector k_F is

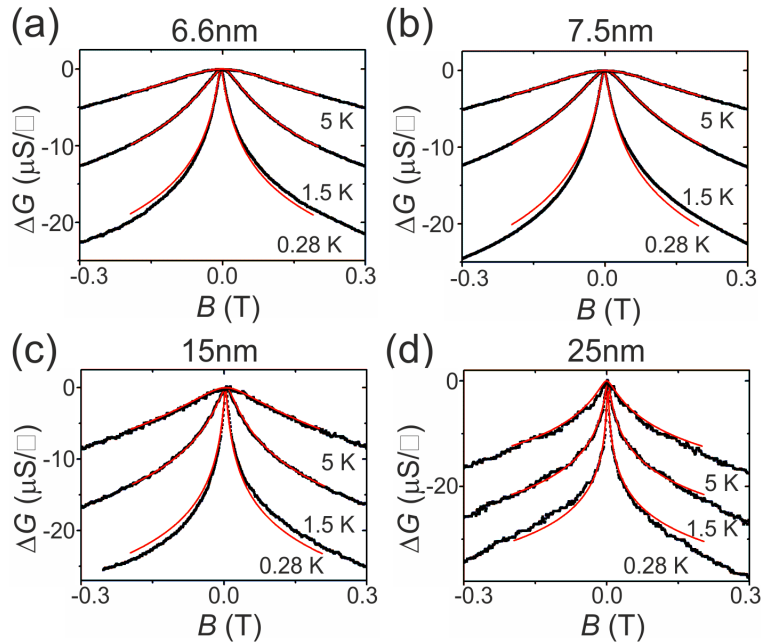


FIG. S1. Weak antilocalization peaks for various Sb_2Te_3 -thicknesses and at 3 different temperatures. Fits to the measurements, based on the HLN model, are shown in straight red lines.

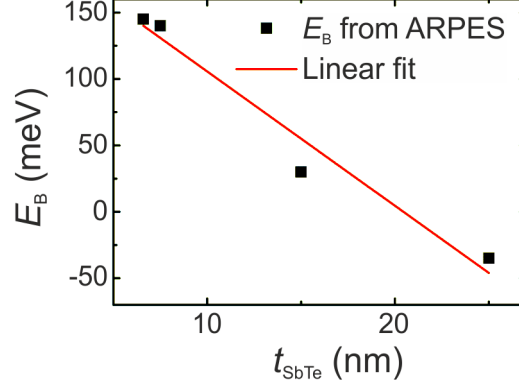


FIG. S2. Relation between E_B and t_{SbTe} (from Ref. [S3])

$$E_B = \beta k_F = \hbar v_F k_F \quad (\text{S3})$$

and can be retrieved from ARPES measurements in Ref. [S3], carried out using samples from the same growth process and identical material parameters. For $E_B = 215 \text{ meV}$, $k_F \approx 0.1 \text{ \AA}^{-1}$ (see Fig. 4(h) in [S3]), thus $\beta = \frac{E_B}{k_F} = 3.44 \cdot 10^{-29} \text{ J m}$. From β , a Fermi velocity of $3.26 \cdot 10^5 \frac{\text{m}}{\text{s}}$ can be derived.

The electron density of the TSS is

$$n_t = k_F^2 / 4\pi = \frac{E_B^2}{4\pi\beta^2} \quad (\text{S4})$$

Furthermore, the relation between E_B and the Sb_2Te_3 -thickness is linear ($dE_B/dt_{\text{SbTe}} = 1.62 \cdot 10^{-12} \text{ J/m}$, see Fig. S2) and

$$n_t = \frac{(dE_B/dt_{\text{SbTe}} \cdot t_{\text{SbTe}})^2}{4\pi\beta^2} \quad (\text{S5})$$

Derivation of the 3-channel model for the Hall resistance

The force acting on charges in the TSS (index t), bulk- Sb_2Te_3 (p) and bulk- Bi_2Te_3 (n) originate from an electric field \vec{E} in y-direction and a magnetic field \vec{B} in z-direction:

$$\begin{aligned} -F_{ny} &= eE_y + ev_{nx}B_z \\ -F_{ty} &= eE_y + ev_{tx}B_z \\ F_{py} &= eE_y - ev_{px}B_z \end{aligned} \quad (\text{S6})$$

Using $v = \frac{\mu}{e} F$ with μ the mobility, we obtain

$$\begin{aligned} \frac{v_{ny}}{\mu_n} &= E_y + \mu_n E_x B_z \\ \frac{v_{ty}}{\mu_t} &= E_y + \mu_t E_x B_z \\ \frac{v_{py}}{\mu_p} &= E_y - \mu_p E_x B_z \end{aligned} \quad (\text{S7})$$

Furthermore, no charge current is flowing in y-direction

$$\begin{aligned} J_y &= J_n + J_t + J_p = en_n v_{ny} + en_t v_{ty} + en_p v_{py} = 0 \\ \implies n v_{ey} &= -(n_t v_{ty} + n_p v_{py}) \end{aligned} \quad (\text{S8})$$

Inserting Eq. S7 in Eq. S8 gives

$$\begin{aligned}
n_n \mu_n (E_y + \mu_n E_x B_z) &= -(n_t \mu_t (E_y + \mu_t E_x B_z) + n_p \mu_p (E_y - \mu_p E_x B_z)) \\
\Rightarrow E_y (n_n \mu_n + n_t \mu_t + n_p \mu_p) &= B_z E_x (-n_n \mu_n^2 - n_t \mu_t^2 + n_p \mu_p^2)
\end{aligned} \tag{S9}$$

The charge current in x-direction is

$$J_x = e n_n v_{nx} + e n_t v_{tx} + e n_p v_{px} = (n_n \mu_n + n_t \mu_t + n_p \mu_p) e E_x \tag{S10}$$

Inserting E_x from S10 into S9 results in

$$\begin{aligned}
e E_y (n_n \mu_n + n_t \mu_t + n_p \mu_p)^2 &= B_z J_x (-n_n \mu_n^2 - n_t \mu_t^2 + n_p \mu_p^2) \\
\Rightarrow R_H = \frac{B_z J_x}{E_y} &= \frac{(-n_n \mu_n^2 - n_t \mu_t^2 + n_p \mu_p^2)}{e (n_n \mu_n + n_t \mu_t + n_p \mu_p)^2}
\end{aligned} \tag{S11}$$

Both n_p and n_t are depending on the thickness of the Sb_2Te_3 -thickness, t_{SbTe} , with

$$\begin{aligned}
n_p &= n_{\text{SbTe}} \cdot t_{\text{SbTe}} \\
n_t(t_{\text{SbTe}}) &= \frac{(dE_B/dt_{\text{SbTe}} \cdot (t_{\text{SbTe}} - t_0))^2}{4\pi\beta^2}
\end{aligned} \tag{S12}$$

(dE/dt_{SbTe} can be gained from Fig. S2 (see section ‘Derivation of TSS charge density’).

Thus $R_H(t_{\text{SbTe}})$ is a function of the Sb_2Te_3 -thickness of the form

$$\begin{aligned}
R_H(t_{\text{SbTe}}) &= \frac{-n_n(t_{\text{SbTe}})\mu_n^2 \pm n_t(t_{\text{SbTe}})\mu_t^2 + n_p\mu_p^2}{e(n_n(t_{\text{SbTe}})\mu_n + n_t(t_{\text{SbTe}})\mu_t + n_p\mu_p)^2} \\
&= \frac{-n_{\text{SbTe}}t_{\text{SbTe}}\mu_n^2 \pm \frac{(dE_B/dt_{\text{SbTe}} \cdot (t_{\text{SbTe}} - t_0))^2}{4\pi\beta^2} \mu_t^2 + n_p\mu_p^2}{e(n_{\text{SbTe}}t_{\text{SbTe}}\mu_n + \frac{(dE_B/dt_{\text{SbTe}} \cdot (t_{\text{SbTe}} - t_0))^2}{4\pi\beta^2} \mu_t + n_p\mu_p)^2}
\end{aligned} \tag{S13}$$

where the ‘+’ sign has to be used when $t_{\text{SbTe}} > 20$ nm and the ‘-’ sign for $t_{\text{SbTe}} < 20$ nm.

Because of the entity $R_H = -1/(e \cdot n_{\text{eff}})$, the ‘effective’ 2-dimensional charge density is given by

$$n_{\text{eff}} = -\frac{(n_n(t_{\text{SbTe}})\mu_n + n_t(t_{\text{SbTe}})\mu_t + n_p\mu_p)^2}{-n_n(t_{\text{SbTe}})\mu_n^2 \pm n_t(t_{\text{SbTe}})\mu_t^2 + n_p\mu_p^2} \tag{S14}$$

Transport characteristics during cooldown

The resistance was recorded during a 2-hour cooldown from 300 K to 300 mK for each sample. The sheet resistances are shown in Fig. S3 for each sample. The thin samples (BST6 and BST7) are initially insulating but show metallic behavior after passing 200 K. The thicker samples are metallic from the start. All samples become insulating at low temperatures of 10 K, the crossover temperature T^* . Although the rise in resistance is less pronounced in the thicker samples, it is still detectable (see inset in Fig. S3(d)). Such an insulating regime at low temperatures is associated with electron-electron interactions (EEI), reducing the electron density at the Fermi edge due to strong Coulomb interactions.

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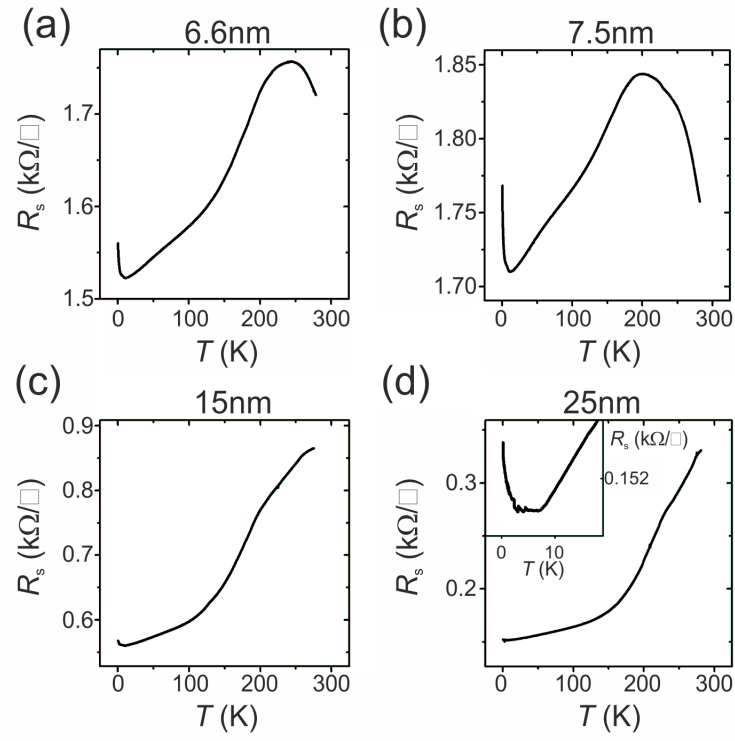


FIG. S3. (a)-(d) Sheet resistance R_s during cooldown for various of Sb_2Te_3 -thicknesses. The inset in (d) shows a magnification of the temperature region below 20 K.